

PATENT APPLICATION

PROTECTED ACTIVE METAL ELECTRODE AND BATTERY CELL STRUCTURES WITH NON-AQUEOUS INTERLAYER ARCHITECTURE

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PROTECTED ACTIVE METAL ELECTRODE AND BATTERY CELL STRUCTURES WITH NON-AQUEOUS INTERLAYER ARCHITECTURE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application No.
5 60/542,532 filed February 6, 2004, titled PROTECTED ACTIVE METAL
ELECTRODE AND BATTERY CELL STRUCTURES WITH NON-AQUEOUS
INTERLAYER ARCHITECTURE; and U.S. Provisional Patent Application No.
60/548,231 filed February 27, 2004, titled VARIATIONS ON PROTECTED ACTIVE
METAL ELECTRODE AND BATTERY CELL STRUCTURES WITH NON-
10 AQUEOUS INTERLAYER ARCHITECTURE; the disclosures of which are
incorporated herein by reference in their entirety and for all purposes.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to active metal electrochemical
15 devices. More particularly, this invention relates to an active metal (e.g., alkali
metals, such as lithium), active metal intercalation (e.g. lithium-carbon, carbon) and
active metal alloys (e.g., lithium-tin) alloys or alloying metals (e.g., tin)
electrochemical (e.g., electrode) structures and battery cells. The electrode structures
have ionically conductive protective architecture including an active metal (e.g.,
20 lithium) conductive impervious layer separated from the electrode (anode) by a porous
separator impregnated with a non-aqueous electrolyte. This protective architecture
prevents the active metal from deleterious reaction with the environment on the other
(cathode) side of the impervious layer, which may include aqueous, air or organic
liquid electrolytes and/or electrochemically active materials.

25 2. Description of Related Art

The low equivalent weight of alkali metals, such as lithium, render them particularly attractive as a battery electrode component. Lithium provides greater energy per volume than the traditional battery standards, nickel and cadmium. Unfortunately, no rechargeable lithium metal batteries have yet succeeded in the market place.

The failure of rechargeable lithium metal batteries is largely due to cell cycling problems. On repeated charge and discharge cycles, lithium “dendrites” gradually grow out from the lithium metal electrode, through the electrolyte, and ultimately contact the positive electrode. This causes an internal short circuit in the battery, rendering the battery unusable after a relatively few cycles. While cycling, lithium electrodes may also grow “mossy” deposits that can dislodge from the negative electrode and thereby reduce the battery’s capacity.

To address lithium’s poor cycling behavior in liquid electrolyte systems, some researchers have proposed coating the electrolyte facing side of the lithium negative electrode with a “protective layer.” Such protective layer must conduct lithium ions, but at the same time prevent contact between the lithium electrode surface and the bulk electrolyte. Many techniques for applying protective layers have not succeeded.

Some contemplated lithium metal protective layers are formed *in situ* by reaction between lithium metal and compounds in the cell’s electrolyte that contact the lithium. Most of these *in situ* films are grown by a controlled chemical reaction after the battery is assembled. Generally, such films have a porous morphology allowing some electrolyte to penetrate to the bare lithium metal surface. Thus, they fail to adequately protect the lithium electrode.

Various pre-formed lithium protective layers have been contemplated. For example, US Patent No. 5,314,765 (issued to Bates on May 24, 1994) describes an *ex situ* technique for fabricating a lithium electrode containing a thin layer of sputtered lithium phosphorus oxynitride (“LiPON”) or related material. LiPON is a glassy single ion conductor (conducts lithium ion) that has been studied as a potential electrolyte for solid state lithium microbatteries that are fabricated on silicon and used to power integrated circuits (See US Patents Nos. 5,597,660, 5,567,210, 5,338,625, and 5,512,147, all issued to Bates et al.).

Work in the present applicants' laboratories has developed technology for the use of glassy or amorphous protective layers, such as LiPON, in active metal battery electrodes. (See, for example, US Patents 6,025,094, issued 02/15/00, 6,402,795, issued 06/11/02, 6,214,061, issued 04/10/01 and 6,413,284, issued 07/02/02, all
5 assigned to PolyPlus Battery Company).

Prior attempts to use lithium anodes in aqueous environments relied either on the use of very basic conditions such as use of concentrated aqueous KOH to slow down the corrosion of the Li electrode, or on the use of polymeric coatings on the Li electrode to impede the diffusion of water to the Li electrode surface. In all cases
10 however, there was substantial reaction of the alkali metal electrode with water. In this regard, the prior art teaches that the use of aqueous cathodes or electrolytes with Li-metal anodes is not possible since the breakdown voltage for water is about 1.2 V and a Li/water cell can have a voltage of about 3.0 V. Direct contact between lithium metal and aqueous solutions results in violent parasitic chemical reaction and
15 corrosion of the lithium electrode for no useful purpose. Thus, the focus of research in the lithium metal battery field has been squarely on the development of effective non-aqueous (mostly organic) electrolyte systems.

SUMMARY OF THE INVENTION

The present invention relates generally to active metal electrochemical devices. More particularly, this invention relates to an active metal (e.g., alkali metals, such as lithium), active metal intercalation (e.g. lithium-carbon, carbon) and
5 active metal alloys (e.g., lithium-tin) alloys or alloying metals (e.g., tin) electrochemical (e.g., electrode) structures and battery cells. The electrochemical structures have ionically conductive protective architecture including an active metal (e.g., lithium) ion conductive substantially impervious layer separated from the electrode (anode) by a porous separator impregnated with a non-aqueous electrolyte
10 (anolyte). This protective architecture prevents the active metal from deleterious reaction with the environment on the other (cathode) side of the impervious layer, which may include aqueous, air or organic liquid electrolytes (catholytes) and/or electrochemically active materials.

The separator layer of the protective architecture prevents deleterious reaction
15 between the active metal (e.g., lithium) of the anode and the active metal ion conductive substantially impervious layer. Thus, the architecture effectively isolates (de-couples) the anode/anolyte from solvent, electrolyte processing and/or cathode environments, including such environments that are normally highly corrosive to Li or other active metals, and at the same time allows ion transport in and out of these
20 potentially corrosive environments.

Various embodiments of the cells and cell structures of the present invention include active metal, active metal-ion, active metal alloying metal, and active metal intercalating anode materials protected with an ionically conductive protective architecture having a non-aqueous anolyte. These anodes may be combined in battery
25 cells with a variety of possible cathode systems, including water, air, metal hydride and metal oxide cathodes and associated catholyte systems, in particular aqueous catholyte systems.

Safety additives may also be incorporated into the structures and cells of the present invention for the case where the substantially impervious layer of the
30 protective architecture (e.g., a glass or glass-ceramic membrane) cracks or otherwise breaks down and allows the aggressive catholyte to enter and approach the lithium electrode. The non-aqueous interlayer architecture can incorporate a

gelling/polymerizing agent that, when in contact with the reactive catholyte, leads to the formation of an impervious polymer on the lithium surface. For example, the anolyte may include a monomer for a polymer that is insoluble or minimally soluble in water, for example dioxolane (Diox)/polydioxaloane and the catholyte may include
5 a polymerization initiator for the monomer, for example, a protonic acid.

In addition, the structures and cells of the present invention may take any suitable form. One advantageous form that facilitates fabrication is a tubular form.

In one aspect, the invention pertains to an electrochemical cell structure. The structure includes an anode composed of an active metal, active metal-ion, active
10 metal alloy, active metal alloying metal or active metal intercalating material. The anode has an ionically conductive protective architecture on its surface. The architecture includes an active metal ion conducting separator layer that has a non-aqueous anolyte and is chemically compatible with the active metal and in contact with the anode, and a substantially impervious ionically conductive layer chemically
15 compatible with the separator layer and aqueous environments and in contact with the separator layer. The separator layer may be, a semi-permeable membrane impregnated with an organic anolyte, for example, a micro-porous polymer impregnated with a liquid or gel phase anolyte. Such an electrochemical (electrode) structure may be paired with a cathode system, including an aqueous cathode system,
20 to form battery cells in accordance with the present invention.

The structures and battery cells incorporating the structures of the present invention may have various configurations, including prismatic and cylindrical, and compositions, including active metal ion, alloy and intercalation anodes, aqueous, water, air, metal hydride and metal oxide cathodes, and aqueous, organic or ionic
25 liquid catholytes; electrolyte (anolyte and/or catholyte) compositions to enhance the safety and/or performance of the cells; and fabrication techniques.

These and other features of the invention are further described and exemplified in the detailed description below.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic illustration of an electrochemical structure cell incorporating an ionically conductive protective interlayer architecture in accordance with the present invention.

Fig. 2 is a schematic illustration of a battery cell incorporating an ionically
5 conductive protective interlayer architecture in accordance with the present invention.

Figs. 3A-C illustrate embodiments of battery cells in accordance with the present invention that use a tubular protected anode design.

Figs. 4-6 are plots of data illustrating the performance of various cells incorporating anodes with ionically conductive protective interlayer architecture in
10 accordance with the present invention.

Fig. 7 illustrates a Li/water battery and hydrogen generator for a fuel cell in accordance with one embodiment of the present invention.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

Reference will now be made in detail to specific embodiments of the invention. Examples of the specific embodiments are illustrated in the accompanying drawings. While the invention will be described in conjunction with these specific
5 embodiments, it will be understood that it is not intended to limit the invention to such specific embodiments. On the contrary, it is intended to cover alternatives, modifications, and equivalents as may be included within the spirit and scope of the invention as defined by the appended claims. In the following description, numerous specific details are set forth in order to provide a thorough understanding of the
10 present invention. The present invention may be practiced without some or all of these specific details. In other instances, well known process operations have not been described in detail in order not to unnecessarily obscure the present invention.

When used in combination with “comprising,” “a method comprising,” “a device comprising” or similar language in this specification and the appended claims,
15 the singular forms “a,” “an,” and “the” include plural reference unless the context clearly dictates otherwise. Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood to one of ordinary skill in the art to which this invention belongs.

Introduction

20 Active metals are highly reactive in ambient conditions and can benefit from a barrier layer when used as electrodes. They are generally alkali metals such (e.g., lithium, sodium or potassium), alkaline earth metals (e.g., calcium or magnesium), and/or certain transitional metals (e.g., zinc), and/or alloys of two or more of these. The following active metals may be used: alkali metals (e.g., Li, Na, K), alkaline
25 earth metals (e.g., Ca, Mg, Ba), or binary or ternary alkali metal alloys with Ca, Mg, Sn, Ag, Zn, Bi, Al, Cd, Ga, In. Preferred alloys include lithium aluminum alloys, lithium silicon alloys, lithium tin alloys, lithium silver alloys, and sodium lead alloys (e.g., Na₄Pb). A preferred active metal electrode is composed of lithium.

The low equivalent weight of alkali metals, such as lithium, render them
30 particularly attractive as a battery electrode component. Lithium provides greater energy per volume than the traditional battery standards, nickel and cadmium.

However, lithium metal or compounds incorporating lithium with a potential near that (e.g., within about a volt) of lithium metal, such as lithium alloy and lithium-ion (lithium intercalation) anode materials, are highly reactive to many potentially attractive electrolyte and cathode materials. This invention describes the use of a non-
5 aqueous electrolyte interlayer architecture to isolate an active metal (e.g., alkali metal, such as lithium), active metal alloy or active metal-ion electrode (usually the anode of a battery cell) from ambient and/or the cathode side of the cell. The architecture includes an active metal ion conducting separator layer with a non-aqueous anolyte (i.e., electrolyte about the anode), the separator layer being chemically compatible
10 with the active metal and in contact with the anode, and a substantially impervious ionically conductive layer chemically compatible with the separator layer and aqueous environments and in contact with the separator layer. The non-aqueous electrolyte interlayer architecture effectively isolates (de-couples) the anode from ambient and/or cathode, including catholyte (i.e., electrolyte about the cathode) environments,
15 including such environments that are normally highly corrosive to Li or other active metals, and at the same time allows ion transport in and out of these potentially corrosive environments. In this way, a great degree of flexibility is permitted the other components of an electrochemical device, such as a battery cell, made with the architecture. Isolation of the anode from other components of a battery cell or other
20 electrochemical cell in this way allows the use of virtually any solvent, electrolyte and/or cathode material in conjunction with the anode. Also, optimization of electrolytes or cathode-side solvent systems may be done without impacting anode stability or performance.

There are a variety of applications that could benefit from the use of aqueous
25 solutions, including water and water-based electrolytes, air, and other materials reactive to lithium and other active metals, including organic solvents/electrolytes and ionic liquids, on the cathode side of the cell with an active (e.g., alkali, e.g., lithium) metal or active metal intercalation (e.g., lithium alloy or lithium-ion) anode in a battery cell.

30 The use of lithium intercalation electrode materials like lithium-carbon and lithium alloy anodes, rather than lithium metal, for the anode can also provide beneficial battery characteristics. First of all, it allows the achievement of prolonged

cycle life of the battery without risk of formation of lithium metal dendrites that can grow from the Li surface to the membrane surface causing the membrane's deterioration. Also, the use of lithium-carbon and lithium alloy anodes in some embodiments of the present invention instead of lithium metal anode can significantly
5 improve a battery's safety because it avoids formation of highly reactive "mossy" lithium during cycling.

The present invention describes a protected active metal, alloy or intercalation electrode that enables very high energy density lithium batteries such as those using aqueous electrolytes or other electrolytes that would otherwise adversely react with
10 lithium metal, for example. Examples of such high energy battery couples are lithium-air, lithium-water lithium-metal hydride, lithium-metal oxide, and the lithium alloy and lithium-ion variants of these. The cells of the invention may incorporate additional components in their electrolytes (anolytes and catholytes) to enhance cell safety, and may have a variety of configurations, including planar and
15 tubular/cylindrical.

Non-Aqueous Interlayer Architecture

The non-aqueous interlayer architecture of the present invention is provided in an electrochemical cell structure, the structure having an anode composed of a material selected from the group consisting of active metal, active metal-ion, active
20 metal alloy, active metal alloying and active metal intercalating material, and an ionically conductive protective architecture on a first surface of the anode. The architecture is composed of an active metal ion conducting separator layer with a non-aqueous anolyte, the separator layer being chemically compatible with the active metal and in contact with the anode, and a substantially impervious ionically conductive
25 layer chemically compatible with the separator layer and aqueous environments and in contact with the separator layer. The separator layer may include a semi-permeable membrane, for example, a micro-porous polymer, such as are available from Celgard, Inc. Charlotte, North Carolina, impregnated with an organic anolyte.

The protective architecture of this invention incorporates a substantially
30 impervious layer of an active metal ion conducting glass or glass-ceramic (e.g., a lithium ion conductive glass-ceramic (LIC-GC)) that has high active metal ion conductivity and stability to aggressive electrolytes that vigorously react with lithium

metal, for example) such as aqueous electrolytes. Suitable materials are substantially impervious, ionically conductive and chemically compatible with aqueous electrolytes or other electrolyte (catholyte) and/or cathode materials that would otherwise adversely react with lithium metal, for example. Such glass or glass-ceramic materials are substantially gap-free, non-swellable and are inherently ionically conductive. That is, they do not depend on the presence of a liquid electrolyte or other agent for their ionically conductive properties. They also have high ionic conductivity, at least 10^{-7} S/cm, generally at least 10^{-6} S/cm, for example at least 10^{-5} S/cm to 10^{-4} S/cm, and as high as 10^{-3} S/cm or higher so that the overall ionic conductivity of the multi-layer protective structure is at least 10^{-7} S/cm and as high as 10^{-3} S/cm or higher. The thickness of the layer is preferably about 0.1 to 1000 microns, or, where the ionic conductivity of the layer is about 10^{-7} S/cm, about 0.25 to 1 micron, or, where the ionic conductivity of the layer is between about 10^{-4} to about 10^{-3} S/cm, about 10 to 1000 microns, preferably between 1 and 500 microns, and more preferably between 10 and 100 microns, for example 20 microns.

Suitable examples of suitable substantially impervious lithium ion conducting layers include glassy or amorphous metal ion conductors, such as a phosphorus-based glass, oxide-based glass, phosphorus-oxynitride-based glass, sulphur-based glass, oxide/sulfide based glass, selenide based glass, gallium based glass, germanium-based glass or boracite glass (such as are described D.P. Button et al., Solid State Ionics, Vols. 9-10, Part 1, 585-592 (December 1983); ceramic active metal ion conductors, such as lithium beta-alumina, sodium beta-alumina, Li superionic conductor (LISICON), Na superionic conductor (NASICON), and the like; or glass-ceramic active metal ion conductors. Specific examples include LiPON, $\text{Li}_3\text{PO}_4\cdot\text{Li}_2\text{S}\cdot\text{SiS}_2$, $\text{Li}_2\text{S}\cdot\text{GeS}_2\cdot\text{Ga}_2\text{S}_3$, $\text{Li}_2\text{O}\cdot 11\text{Al}_2\text{O}_3$, $\text{Na}_2\text{O}\cdot 11\text{Al}_2\text{O}_3$, $(\text{Na}, \text{Li})_{1+x}\text{Ti}_{2-x}\text{Al}_x(\text{PO}_4)_3$ ($0.6 \leq x \leq 0.9$) and crystallographically related structures, $\text{Na}_3\text{Zr}_2\text{Si}_2\text{PO}_{12}$, $\text{Li}_3\text{Zr}_2\text{Si}_2\text{PO}_{12}$, $\text{Na}_5\text{ZrP}_3\text{O}_{12}$, $\text{Na}_5\text{TiP}_3\text{O}_{12}$, $\text{Na}_3\text{Fe}_2\text{P}_3\text{O}_{12}$, $\text{Na}_4\text{NbP}_3\text{O}_{12}$, $\text{Li}_5\text{ZrP}_3\text{O}_{12}$, $\text{Li}_5\text{TiP}_3\text{O}_{12}$, $\text{Li}_3\text{Fe}_2\text{P}_3\text{O}_{12}$ and $\text{Li}_4\text{NbP}_3\text{O}_{12}$, and combinations thereof, optionally sintered or melted. Suitable ceramic ion active metal ion conductors are described, for example, in US Patent No. 4,985,317 to Adachi *et al.*, incorporated by reference herein in its entirety and for all purposes.

A particularly suitable glass-ceramic material for the substantially impervious layer of the protective architecture is a lithium ion conductive glass-ceramic having the following composition:

Composition	mol %
P_2O_5	26-55%
SiO_2	0-15%
$GeO_2 + TiO_2$	25-50%
in which GeO_2	0--50%
TiO_2	0--50%
ZrO_2	0-10%
M_2O_3	$0 < 10\%$
Al_2O_3	0-15%
Ga_2O_3	0-15%
Li_2O	3-25%

5

and containing a predominant crystalline phase composed of $Li_{1+x}(M,Al,Ga)_x(Ge_{1-y}Ti_y)_{2-x}(PO_4)_3$ where $X \leq 0.8$ and $0 \leq Y \leq 1.0$, and where M is an element selected from the group consisting of Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm and Yb and/or and $Li_{1+x+y}Q_xTi_{2-x}Si_yP_{3-y}O_{12}$ where $0 < X \leq 0.4$ and $0 < Y \leq 0.6$, and where Q is Al or Ga.

10 The glass-ceramics are obtained by melting raw materials to a melt, casting the melt to a glass and subjecting the glass to a heat treatment. Such materials are available from OHARA Corporation, Japan and are further described in US Patent Nos. 5,702,995, 6,030,909, 6,315,881 and 6,485,622, incorporated herein by reference.

Such lithium ion conductive substantially impervious layers and techniques for
 15 their fabrication and incorporation in battery calls are described in U.S. Provisional Patent Application No. 60/418,899, filed October 15, 2002, titled IONICALLY CONDUCTIVE COMPOSITES FOR PROTECTION OF ANODES AND ELECTROLYTES, its

corresponding US Patent application No. 10/686,189 (Attorney Docket No. PLUSP027), filed October 14, 2003, and titled IONICALLY CONDUCTIVE COMPOSITES FOR PROTECTION OF ACTIVE METAL ANODES, US Patent application No. 10/731,771 (Attorney Docket No. PLUSP027X1), filed December 5, 2003, and titled IONICALLY
5 CONDUCTIVE COMPOSITES FOR PROTECTION OF ACTIVE METAL ANODES, and US Patent application No. 10/772,228 (Attorney Docket No. PLUSP039), filed February 3, 2004, and titled IONICALLY CONDUCTIVE MEMBRANES FOR PROTECTION OF ACTIVE METAL ANODES AND BATTERY CELLS. These applications are incorporated by reference herein in their entirety for all purposes.

10 A critical limitation in the use of these highly conductive glasses and glass-ceramics in lithium (or other active metal or active metal intercalation) batteries is their reactivity to lithium metal or compounds incorporating lithium with a potential near that (e.g., within about a volt) of lithium metal. The non-aqueous electrolyte interlayer of the present invention isolates the lithium (for example) electrode from
15 reacting with the glass or glass-ceramic membrane. The non-aqueous interlayer may have a semi-permeable membrane, such as a Celgard micro-porous separator, to prevent mechanical contact of the lithium electrode to the glass or glass-ceramic membrane. The membrane is impregnated with organic liquid electrolyte (anolyte) with solvents such as ethylene carbonate (EC), propylene carbonate (PC), 1,2-
20 dimethoxy ethane (DME), 1,3-dioxolane (DIOX), or various ethers, glymes, lactones, sulfones, sulfolane, or mixtures thereof. It may also or alternatively have a polymer electrolyte, a gel-type electrolyte, or a combination of these. The important criteria are that the lithium electrode is stable in the non-aqueous anolyte, the non-aqueous anolyte is sufficiently conductive to Li^+ ions, the lithium electrode does not directly
25 contact the glass or glass-ceramic membrane, and the entire assembly allows lithium ions to pass through the glass or glass-ceramic membrane.

Referring to Fig. 1, a specific embodiment of the present invention is illustrated and described. Fig. 1 shows an unscaled depiction of an electrochemical cell structure 100 having an active metal, active metal-ion, active metal alloying
30 metal, or active metal intercalating material anode 102 and an ionically conductive protective architecture 104. The protective architecture 104 has an active metal ion conducting separator layer 106 with a non-aqueous anolyte (sometimes also referred

to as a transfer electrolyte) on a surface of the anode 102 and a substantially impervious ionically conductive layer 108 in contact with the separator layer 106. The separator layer 106 is chemically compatible with the active metal and the substantially impervious layer 108 is chemically compatible with the separator layer 106 and aqueous environments. The structure 100 may optionally include a current collector 110, composed of a suitable conductive metal that does not alloy with or intercalate the active metal. When the active metal is lithium, a suitable current collector material is copper. The current collector 110 can also serve to seal the anode from ambient to prevent deleterious reaction of the active metal with ambient air or moisture.

The separator layer 106 is composed of a semi-permeable membrane impregnated with an organic anolyte. For example, the semi-permeable membrane may be a micro-porous polymer, such as are available from Celgard, Inc. The organic anolyte may be in the liquid or gel phase. For example, the anolyte may include a solvent selected from the group consisting of organic carbonates, ethers, lactones, sulfones, etc, and combinations thereof, such as EC, PC, DEC, DMC, EMC, 1,2-DME or higher glymes, THF, 2MeTHF, sulfolane, and combinations thereof. 1,3-dioxolane may also be used as an anolyte solvent, particularly but not necessarily when used to enhance the safety of a cell incorporating the structure, as described further below. When the anolyte is in the gel phase, gelling agents such as polyvinylidene fluoride (PVdF) compounds, hexafluoropropylene-vinylidene fluoride copolymers (PVdf-HFP), polyacrylonitrile compounds, cross-linked polyether compounds, polyalkylene oxide compounds, polyethylene oxide compounds, and combinations and the like may be added to gel the solvents. Suitable anolytes will also, of course, also include active metal salts, such as, in the case of lithium, for example, LiPF_6 , LiBF_4 , LiAsF_6 , LiSO_3CF_3 or $\text{LiN}(\text{SO}_2\text{C}_2\text{F}_5)_2$. One example of a suitable separator layer is 1 M LiPF_6 dissolved in propylene carbonate and impregnated in a Celgard microporous polymer membrane.

There are a number of advantages of a protective architecture in accordance with the present invention. In particular, cell structures incorporating such an architecture may be relatively easily manufactured. In one example, lithium metal is simply placed against a micro-porous separator impregnated with organic liquid or gel

electrolyte and with the separator adjacent to a glass/glass ceramic active metal ion conductor.

An additional advantage of the non-aqueous interlayer is realized when glass-ceramics are used. When amorphous glasses of the type described by the OHARA Corp. patents cited above are heat-treated, the glass devitrifies, leading to the formation of a glass-ceramic. However, this heat treatment can lead to the formation of surface roughness which may be difficult to coat using vapor phase deposition of an inorganic protective interlayer such as LiPON, Cu₃N, etc. The use of a liquid (or gel), non-aqueous electrolyte interlayer would easily cover such a rough surface by normal liquid flow, thereby eliminating the need for surface polishing, etc. In this sense, techniques such as “draw-down” (as described by Sony Corporation and Shott Glass (T. Kessler, H. Wegener, T. Togawa, M. Hayashi, and T. Kakizaki, “Large Microsheet Glass for 40-in. Class PALC Displays,” 1997, FMC2-3, downloaded from Shott Glass website; <http://www.schott.com/english>, incorporated herein by reference) could be used to form thin glass layers (20 to 100 microns), and these glasses heat treated to form glass-ceramics.

Battery Cells

The non-aqueous interlayer architecture is usefully adopted in battery cells. For example, the electrochemical structure 100 of Fig. 1 can be paired with a cathode system 120 to form a cell 200, as depicted in Fig. 2. The cathode system 120 includes an electronically conductive component, an ionically conductive component, and an electrochemically active component. The cathode system 120 may have any desired composition and, due to the isolation provided by the protective architecture, is not limited by the anode or anolyte composition. In particular, the cathode system may incorporate components which would otherwise be highly reactive with the anode active metal, such as aqueous materials, including water, aqueous catholytes and air, metal hydride electrodes and metal oxide electrodes.

In one embodiment, a Celgard separator would be placed against one side of the thin glass-ceramic, followed by a non-aqueous liquid or gel electrolyte, and then a lithium electrode. On the other side of the glass ceramic membrane, an aggressive solvent could be used, such as an aqueous electrolyte. In such a way, an inexpensive Li/water or Li/air cell, for example, could be built.

Cathode Systems

As noted above, the cathode system 120 of a battery cell in accordance with the present invention may have any desired composition and, due to the isolation provided by the protective architecture, is not limited by the anode or anolyte composition. In particular, the cathode system may incorporate components which would otherwise be highly reactive with the anode active metal, such as aqueous materials, including water, aqueous solutions and air, metal hydride electrodes and metal oxide electrodes.

Battery cells of the present invention may include, without limitation, water, aqueous solutions, air electrodes and metal hydride electrodes, such as are described in co-pending application No. 10/772,157 titled ACTIVE METAL/AQUEOUS ELECTROCHEMICAL CELLS AND SYSTEMS, incorporated herein by reference in its entirety and for all purposes, and metal oxide electrodes, as used, for example, in conventional Li-ion cells.

The effective isolation between anode and cathode achieved by the protective interlayer architecture of the present invention also enables a great degree of flexibility in the choice of catholyte systems, in particular aqueous systems, but also non-aqueous systems. Since the protected anode is completely decoupled from the catholyte, so that catholyte compatibility with the anode is no longer an issue, solvents and salts which are not kinetically stable to Li can be used.

For cells using water as an electrochemically active cathode material, a porous electronically conductive support structure can provide the electronically conductive component of the cathode system. An aqueous electrolyte (catholyte) provides ion carriers for transport (conductivity) of Li ions and anions that combine with Li. The electrochemically active component (water) and the ionically conductive component (aqueous catholyte) will be intermixed as a single solution, although they are conceptually separate elements of the battery cell. Suitable catholytes for the Li/water battery cell of the invention include any aqueous electrolyte with suitable ionic conductivity. Suitable electrolytes may be acidic, for example, strong acids like HCl, H₂SO₄, H₃PO₄ or weak acids like acetic acid/Li acetate; basic, for example, LiOH; neutral, for example, sea water, LiCl, LiBr, LiI; or amphoteric, for example, NH₄Cl, NH₄Br, etc

The suitability of sea water as an electrolyte enables a battery cell for marine applications with very high energy density. Prior to use, the cell structure is composed of the protected anode and a porous electronically conductive support structure (electronically conductive component of the cathode). When needed, the cell is completed by immersing it in sea water which provides the electrochemically active and ionically conductive components. Since the latter components are provided by the sea water in the environment, they need not be transported as part of the battery cell prior to its use (and thus need not be included in the cell's energy density calculation). Such a cell is referred to as an "open" cell since the reaction products on the cathode side are not contained. Such a cell is, therefore, a primary cell.

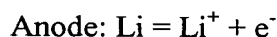
Secondary Li/water cells are also possible in accordance with the invention. As noted above, such cells are referred to as "closed" cells since the reaction products on the cathode side are contained on the cathode side of the cell to be available to recharge the anode by moving the Li ions back across the protective membrane when the appropriate recharging potential is applied to the cell.

As noted above and described further below, in another embodiment of the invention, ionomers coated on the porous catalytic electronically conductive support reduce or eliminate the need for ionic conductivity in the electrochemically active material.

The electrochemical reaction that occurs in a Li/water cell is a redox reaction in which the electrochemically active cathode material gets reduced. In a Li/water cell, the catalytic electronically conductive support facilitates the redox reaction. As noted above, while not so limited, in a Li/water cell, the cell reaction is believed to be:



The half-cell reactions at the anode and cathode are believed to be:



Accordingly, the catalyst for the Li/water cathode promotes electron transfer to water, generating hydrogen and hydroxide ion. A common, inexpensive catalyst for

this reaction is nickel metal; precious metals like Pt, Pd, Ru, Au, etc. will also work but are more expensive.

Also considered to be within the scope of Li (or other active metal)/water batteries of this invention are batteries with a protected Li anode and an aqueous electrolyte composed of gaseous and/or solid oxidants soluble in water that can be used as active cathode materials (electrochemically active component). Use of water soluble compounds, which are stronger oxidizers than water, can significantly increase battery energy in some applications compared to the lithium/water battery, where during the cell discharge reaction, electrochemical hydrogen evolution takes place at the cathode surface. Examples of such gaseous oxidants are O_2 , SO_2 and NO_2 . Also, metal nitrites, in particular $NaNO_2$ and KNO_2 and metal sulfites such as Na_2SO_3 and K_2SO_3 are stronger oxidants than water and can be easily dissolved in large concentrations. Another class of inorganic oxidants soluble in water are peroxides of lithium, sodium and potassium, as well as hydrogen peroxide H_2O_2 .

The use of hydrogen peroxide as an oxidant can be especially beneficial. There are at least two ways of utilizing hydrogen peroxide in a battery cell in accordance with the present invention. First of all, chemical decomposition of hydrogen peroxide on the cathode surface leads to production of oxygen gas, which can be used as active cathode material. The second, perhaps more effective way, is based on the direct electroreduction of hydrogen peroxide on the cathode surface. In principal, hydrogen peroxide can be reduced from either basic or acidic solutions. The highest energy density can be achieved for a battery utilizing hydrogen peroxide reduction from acidic solutions. In this case a cell with Li anode yields $E^0 = 4.82$ V (for standard conditions) compared to $E^0 = 3.05$ V for Li/Water couple. However, because of very high reactivity of both acids and hydrogen peroxide to unprotected Li, such cell can be practically realized only for protected Li anode such as in accordance with the present invention.

For cells using air as an electrochemically active cathode material, the air electrochemically active component of these cells includes moisture to provide water for the electrochemical reaction. The cells have an electronically conductive support structure electrically connected with the anode to allow electron transfer to reduce the air cathode active material. The electronically conductive support structure is

generally porous to allow fluid (air) flow and either catalytic or treated with a catalyst to catalyze the reduction of the cathode active material. An aqueous electrolyte with suitable ionic conductivity or ionomer is also in contact with the electronically conductive support structure to allow ion transport within the electronically conductive support structure to complete the redox reaction.

The air cathode system includes an electronically conductive component (for example, a porous electronic conductor), an ionically conductive component with at least an aqueous constituent, and air as an electrochemically active component. It may be any suitable air electrode, including those conventionally used in metal (e.g., Zn)/air batteries or low temperature (e.g., PEM) fuel cells. Air cathodes used in metal/air batteries, in particular in Zn/air batteries, are described in many sources including "Handbook of Batteries" (Linden and T. B. Reddy, McGraw-Hill, NY, Third Edition) and are usually composed of several layers including an air diffusion membrane, a hydrophobic Teflon layer, a catalyst layer, and a metal electronically conductive component/current collector, such as a Ni screen. The catalyst layer also includes an ionically conductive component/electrolyte that may be aqueous and/or ionomeric. A typical aqueous electrolyte is composed of KOH dissolved in water. An typical ionomeric electrolyte is composed of a hydrated (water) Li ion conductive polymer such as a per-fluoro-sulfonic acid polymer film (e.g., du Pont NAFION). The air diffusion membrane adjusts the air (oxygen) flow. The hydrophobic layer prevents penetration of the cell's electrolyte into the air-diffusion membrane. This layer usually contains carbon and Teflon particles. The catalyst layer usually contains a high surface area carbon and a catalyst for acceleration of reduction of oxygen gas. Metal oxides, for example MnO_2 , are used as the catalysts for oxygen reduction in most of the commercial cathodes. Alternative catalysts include metal macrocycles such as cobalt phthalocyanine, and highly dispersed precious metals such as platinum and platinum/ruthenium alloys. Since the air electrode structure is chemically isolated from the active metal electrode, the chemical composition of the air electrode is not constrained by potential reactivity with the anode active material. This can allow for the design of higher performance air electrodes using materials that would normally attack unprotected metal electrodes.

Another type of active metal/aqueous battery cell incorporating a protected anode and a cathode system with an aqueous component in accordance with the present invention is a lithium (or other active metal)/metal hydride battery. For example, lithium anodes protected with a non-aqueous interlayer architecture as described herein can be discharged and charged in aqueous solutions suitable as electrolytes in a lithium/metal hydride battery. Suitable electrolytes provide a source or protons. Examples include aqueous solutions of halide acids or acidic salts, including chloride or bromide acids or salts, for example HCl, HBr, NH₄Cl or NH₄Br.

In addition to the aqueous, air, etc., systems noted above, improved performance can be obtained with cathode systems incorporating conventional Li-ion battery cathodes and electrolytes, such as metal oxide cathodes (e.g., Li_xCoO₂, Li_xNiO₂, Li_xMn₂O₄ and LiFePO₄) and the binary, ternary or multicomponent mixtures of alkyl carbonates or their mixtures with ethers as solvents for a Li metal salt (e.g., LiPF₆, LiAsF₆ or LiBF₄); or Li metal battery cathodes (e.g., elemental sulfur or polysulfides) and electrolytes composed of organic carbonates, ethers, glymes, lactones, sulfones, sulfolane, and combinations thereof, such as EC, PC, DEC, DMC, EMC, 1,2-DME, THF, 2MeTHF, and combinations thereof, as described, for example, in US Patent No. 6,376,123, incorporated herein by reference.

Moreover, the catholyte solution can be composed of only low viscosity solvents, such as ethers like 1,2-dimethoxy ethane (DME), tetrahydrofuran (THF), 2-methyltetrahydrofuran, 1,3-dioxolane (DIOX), 4-methyldioxolane (4-MeDIOX) or organic carbonates like dimethylcarbonate (DMC), ethylmethylcarbonate (EMC), diethylcarbonate (DEC), or their mixtures. Also, super low viscosity ester solvents or co-solvents such as methyl formate and methyl acetate, which are very reactive to unprotected Li, can be used. As is known to those skilled in the art, ionic conductivity and diffusion rates are inversely proportional to viscosity such that all other things being equal, battery performance improves as the viscosity of the solvent decreases. The use of such catholyte solvent systems significantly improves battery performance, in particular discharge and charge characteristics at low temperatures.

Ionic liquids may also be used in catholytes of the present invention. Ionic liquids are organic salts with melting points under 100 degrees, often even lower than room temperature. The most common ionic liquids are imidazolium and pyridinium

derivatives, but also phosphonium or tetralkylammonium compounds are also known. Ionic liquids have the desirable attributes of high ionic conductivity, high thermal stability, no measurable vapor pressure, and non-flammability. Representative ionic liquids are 1-Ethyl-3-methylimidazolium tosylate (EMIM-Ts), 1-Butyl-3-methylimidazolium octyl sulfate (BMIM-OctSO₄), 1-Ethyl-3-methylimidazolium hexafluorophosphate, and 1-Hexyl-3-methylimidazolium tetrafluoroborate. Although there has been substantial interest in ionic liquids for electrochemical applications such as capacitors and batteries, they are unstable to metallic lithium and lithiated carbon. However, protected lithium anodes as described in this invention are isolated from direct chemical reaction, and consequently lithium metal batteries using ionic liquids are possible as an embodiment of the present invention. Such batteries should be particularly stable at elevated temperatures.

Safety Additives

As a safety measure, the non-aqueous interlayer architecture can incorporate a gelling/polymerizing agent that, when in contact with the reactive electrolyte (for example water), leads to the formation of an impervious polymer on the anode (e.g., lithium) surface. This safety measure is used for the case where the substantially impervious layer of the protective architecture (e.g., a glass or glass-ceramic membrane) cracks or otherwise breaks down and allows the aggressive catholyte to enter and approach the lithium electrode raising the possibility of a violent reaction between the Li anode and aqueous catholyte.

Such a reaction can be prevented by providing in the anolyte a monomer for a polymer that is insoluble or minimally soluble in water, for example dioxolane (Diox) (for example, in an amount of about 5-20% by volume) and in the catholyte a polymerization initiator for the monomer, for example, a protonic acid. A Diox based anolyte may be composed of organic carbonates (EC, PC, DEC, DMC, EMC), ethers (1, 2-DME, THF, 2MeTHF, 1,3-dioxolane and others) and their mixtures. Anolyte comprising dioxolane as a main solvent (e.g., 50-100% by volume) and Li salt, in particular, LiAsF₆, LiBF₄, LiSO₃CF₃, LiN(SO₂C₂F₅)₂, is especially attractive. Diox is a good passivating agent for Li surface, and good cycling data for Li metal has been achieved in the Diox based electrolytes (see, e.g., US Patent 5,506,068). In addition

to its compatibility with Li metal, Diox in combination with above-mentioned ionic salts forms highly conductive electrolytes. A corresponding aqueous catholyte contains a polymerization initiator for Diox that produces a Diox polymerization product (polydioxolane) that is not or is only minimally soluble in water.

5 If the membrane breaks down, the catholyte containing the dissolved initiator comes in direct contact with the Diox based anolyte, and polymerization of Diox occurs next to the Li anode surface. Polydioxolane, which is a product of Diox polymerization, has high resistance, so the cell shuts down. In addition, the Polydioxolane layer formed serves as a barrier preventing reaction between the Li
10 surface and the aqueous catholyte. Diox can be polymerized with protonic acids dissolved in the catholyte. Also, the water soluble Lewis acids, in particular benbenzoyl cation, can serve this purpose.

 Thus, improvement in cyclability and safety is achieved by the use of a dioxolane (Diox) based anolyte and a catholyte containing a polymerization initiator
15 for Diox.

Active Metal Ion and Alloy Anodes

 The invention pertains to batteries and other electrochemical structures having anodes composed of active metals, as described above. A preferred active metal electrode is composed of lithium (Li). Suitable anolytes for these structures and cells
20 are described above.

 The invention also pertains to electrochemical structures having active metal ion (e.g., lithium-carbon) or active metal alloy (e.g., Li-Sn) anodes. Some structures may initially have uncharged active metal ion intercalation materials (e.g., carbon) or alloying metals (e.g., tin (Sn)) that are subsequently charged with active metal or
25 active metal ions. While the invention may be applicable to a variety of active metals, it is described herein primarily with reference to lithium, as an example.

 Carbon materials commonly used in conventional Li-ion cells, in particular petroleum coke and mesocarbon microbead carbons, can be used as anode materials in Li-ion aqueous battery cells. Lithium alloys comprising one or several of the metals
30 selected from the group including Ca, Mg, Sn, Ag, Zn, Bi, Al, Cd, Ga, In and Sb,

preferably Al, Sn or Si, can also be used as anode materials for such a battery. In one particular embodiment the anode comprises Li, Cu and Sn.

Anolyte for such structures can incorporate supporting salts, for example, LiPF_6 , LiBF_4 , LiAsF_6 , LiClO_4 , LiSO_3CF_3 , $\text{LiN}(\text{CF}_3\text{SO}_2)_2$ or $\text{LiN}(\text{SO}_2\text{C}_2\text{F}_5)_2$ dissolved
 5 in binary or ternary mixtures of non-aqueous solvents, for example, EC, PC, DEC, DMC, EMC, MA, MF, commonly used in conventional Li-ion cells. Gel-polymer electrolytes, for instance electrolytes comprising one of the above mentioned salts, a polymeric binder, such as PVdF, PVdF-HFP copolymer, PAN or PEO, and a plasticizer (solvent) such as EC, PC, DEC, DMC, EMC, THF, 2MeTHF, 1,2-DME
 10 and their mixtures, also can be used.

For batteries using these anodes, a suitable cathode structure may be added to the electrochemical structure on the other side of the protective architecture. The architecture enables Li-ion type cells using a number of exotic cathodes such as air, water, metal hydrides or metal oxides. For Li-ion aqueous battery cells, for example,
 15 aqueous catholyte can be basic, acidic or neutral and contains Li cations. One example of a suitable aqueous catholyte is 2 M LiCl, 1 M HCl.

During the first charge of the battery with lithium-carbon lithium alloy anode, Li cations are transported from the catholyte through the protective architecture (including the anolyte) to the anode surface where the intercalation process takes place
 20 as in conventional Li-ion cells. In one embodiment, the anode is chemically or electrochemically lithiated *ex-situ* before cell assembly.

Cell designs

Electrochemical structures and battery cells in accordance with the present invention may have any suitable geometry. For example, planar geometries may be
 25 achieved by stacking planar layers of the various components of the structures or cells (anode, interlayer, cathode, etc.) according to known battery cell fabrication techniques that are readily adaptable to the present invention given the description of the structure or cell components provided herein. These stacked layers may be configured as prismatic structures or cells.

30 Alternatively, the use of tubular glass or glass-ceramic electrolytes with a non-aqueous interlayer architecture allows for the construction of high surface area anodes

with low seal area. As opposed to flat-plate design where the seal length increases with cell surface area, tubular construction utilizes an end seal where the length of the tube can be increased to boost surface area while the seal area is invariant. This allows for the construction of high surface area Li/water and Li/air cells that should
5 have correspondingly high power density.

The use of a non-aqueous interlayer architecture in accordance with the present invention facilitates construction. An open-ended (with a seal) or close-ended glass or glass-ceramic (i.e., substantially impervious active metal ion conductive solid electrolyte) tube is partially filled with a non-aqueous organic electrolyte (anolyte or
10 transfer electrolyte) as described above, for example such as is typically used in lithium primary batteries. A lithium metal rod surrounded by some type of physical separator (e.g., a semi-permeable polymer film such as Celgard, Tonin, polypropylene mesh, etc.) having a current collector is inserted into the tube. A simple epoxy seal, glass-to-metal seal, or other appropriate seal is used to physically isolate the lithium
15 from the environment.

The protected anode can then be inserted in a cylindrical air electrode to make a cylindrical cell, as shown in Fig. 3A. Or an array of anodes might be inserted into a prismatic air electrode, as shown in Fig. 3B.

This technology can also be used to build Li/water, Li/metal hydride or
20 Li/metal oxide cells by substituting the air electrode with suitable aqueous, metal hydride or metal oxide cathode systems, as described herein above.

In addition to the use of lithium metal rods or wires (in capillary tubes), this invention can also be used to isolate a rechargeable LiC_x anode from aqueous or otherwise corrosive environments. In this case, appropriate anolyte (transfer
25 electrolyte) solvents are used in the tubular anode to form a passive film on the lithiated carbon electrode. This would allow the construction of high surface area Li-ion type cells using a number of exotic cathodes such as air, water, metal hydrides or metal oxides, for example, as shown in Fig. 3C.

Examples

30 The following examples provide details illustrating advantageous properties of Li metal and Li-ion aqueous battery cells in accordance with the present invention.

These examples are provided to exemplify and more clearly illustrate aspects of the present invention and in no way intended to be limiting.

Example 1: Li/Seawater Cell

A series of experiments was performed in which the commercial ionically
 5 conductive glass-ceramic from OHARA Corporation was used as a membrane
 separating aqueous catholyte and non-aqueous anolyte. The cell structure was Li/non-
 aqueous electrolyte/glass-ceramic/aqueous electrolyte/Pt. A lithium foil from
 Chemetall Foote Corporation with thickness of 125 microns was used as the anode.
 The GLASS-CERAMIC plates were in the range of 0.3 to 0.48 mm in thickness. The
 10 GLASS-CERAMIC plate was fitted into an electrochemical cell by use of two o-rings
 such that the GLASS-CERAMIC plate was exposed to an aqueous environment from
 one side and a non-aqueous environment from the other side. In this case, the aqueous
 electrolyte comprised an artificial seawater prepared with 35 ppt of "Instant Ocean"
 from Aquarium Systems, Inc. The conductivity of the seawater was determined to be
 15 $4.5 \cdot 10^{-2}$ S/cm. A microporous Celgard separator placed on the other side of the
 GLASS-CERAMIC was filled with non-aqueous electrolyte comprised of 1 M LiPF_6
 dissolved in propylene carbonate. The loading volume of the nonaqueous electrolyte
 was 0.25 ml per 1 cm^2 of Li electrode surface. A platinum counter electrode
 completely immersed in the sea water catholyte was used to facilitate hydrogen
 20 reduction when the battery circuit was completed. An Ag/AgCl reference electrode
 was used to control potential of the Li anode in the cell. Measured values were
 recalculated into potentials in the Standard Hydrogen Electrode (SHE) scale. An open
 circuit potential (OCP) of 3.05 volts corresponding closely to the thermodynamic
 potential difference between Li/Li^+ and H_2/H^+ in water was observed (Fig. 4). When
 25 the circuit was closed, hydrogen evolution was seen immediately at the Pt electrode,
 which was indicative of the anode and cathode electrode reactions in the cell, $2\text{Li} =$
 $2\text{Li} + 2\text{e}^-$ and $2\text{H}^+ + 2\text{e}^- = \text{H}_2$. The potential-time curve for Li anodic dissolution at a
 discharge rate of 0.3 mA/cm^2 is presented in Fig. 2. The results indicate an
 operational cell with a stable discharge voltage. It should be emphasized that in all
 30 experiments using a Li anode in direct contact with seawater utilization of Li was very
 poor, and such batteries could not be used at all at low and moderate current densities

similar to those used in this example due to the extremely high rate of Li corrosion in seawater (over 19 A/cm²).

Example 2: Li/Air Cell

The cell structure was similar to that in the previous example, but instead of a Pt electrode completely immersed in the electrolyte, this experimental cell had an air electrode made for commercial Zn/Air batteries. An aqueous electrolyte used was 1 M LiOH. A Li anode and a non-aqueous electrolyte were the same as described in the previous example.

An open circuit potential of 3.2 V was observed for this cell. Fig. 5 shows discharge voltage-time curve at discharge rate of 0.3 mA/cm². The cell exhibited discharge voltage of 2.8-2.9 V. for more than 14 hrs. This result shows that good performance can be achieved for Li/air cells with solid electrolyte membrane separating aqueous catholyte and non-aqueous anolyte.

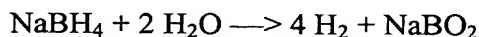
Example 3: Li-ion Cell.

In these experiments the commercial ionically conductive glass-ceramic from OHARA Corporation was used as a membrane separating aqueous catholyte and non-aqueous anolyte. The cell structure was carbon/non-aqueous electrolyte/glass-ceramic plate/aqueous electrolyte/Pt. A commercial carbon electrode on copper substrate comprising a synthetic graphite similar to carbon electrodes commonly used in lithium-ion batteries was used as the anode. The thickness of the glass-ceramic plate was 0.3 mm. The glass-ceramic plate was fitted into an electrochemical cell by use of two o-rings such that the glass-ceramic plate was exposed to an aqueous environment from one side and a non-aqueous environment from the other side. The aqueous electrolyte comprised 2 M LiCl and 1 M HCl. Two layers of microporous Celgard separator placed on the other side of the glass-ceramic were filled with non-aqueous electrolyte comprised of 1 M LiPF₆ dissolved in the mixture of ethylene carbonate and dimethyl carbonate (1:1 by volume). A lithium wire reference electrode was placed between two layers of Celgard separator in order to control the potential of the carbon anode during cycling. A platinum mesh completely immersed in the 2 M LiCl, 1 M HCl solution was used as the cell cathode. An Ag/AgCl reference electrode placed in the aqueous electrolyte was used to control potential of the carbon electrode and

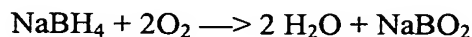
voltage drop across the GLASS-CERAMIC plate, as well as potential of the Pt cathode during cycling. An open circuit voltage (OCV) around 1 volt was observed for this cell. The voltage difference of 3.2 volts between Li reference electrode and Ag/AgCl reference electrode closely corresponding to the thermodynamical value was observed. The cell was charged at 0.1 mA/cm² until the carbon electrode potential reached 5 mV vs. Li reference electrode, and then at 0.05 mA/cm² using the same cutoff potential. The discharge rate was 0.1 mA/cm², and discharge cutoff potential for the carbon anode was 1.8 V vs. Li reference electrode. The data in Fig. 6 show that the cell with intercalation carbon anode and aqueous electrolyte containing Li cations can work reversibly. This is the first known example where aqueous solution has been used in Li-ion cell instead of solid lithiated oxide cathode as a source of Li ions for charging of the carbon anode.

Alternative Embodiment - Li/Water Battery and Hydrogen Generator for Fuel Cell

The use of protective architecture on active metal electrodes in accordance with the present invention allows the construction of active metal/water batteries that have negligible corrosion currents, described above. The Li/water battery has a very high theoretical energy density of 8450 Wh/kg. The cell reaction is $\text{Li} + \text{H}_2\text{O} = \text{LiOH} + 1/2 \text{H}_2$. Although the hydrogen produced by the cell reaction is typically lost, in this embodiment of the present invention it is used to provide fuel for an ambient temperature fuel cell. The hydrogen produced can be either fed directly into the fuel cell or it can be used to recharge a metal hydride alloy for later use in a fuel cell. At least one company, Millenium Cell <<<http://www.millenniumcell.com/news/tech.html>>> makes use of the reaction of sodium borohydride with water to produce hydrogen. However, this reaction requires the use of a catalyst, and the energy produced from the chemical reaction of NaBH₄ and water is lost as heat.



When combined with the fuel cell reaction, $\text{H}_2 + \text{O}_2 = \text{H}_2\text{O}$, the full cell reaction is believed to be:

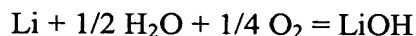


The energy density for this system can be calculated from the equivalent weight of the NaBH₄ reactant (38/4 = 9.5 grams/equiv.). The gravimetric capacity of NaBH₄ is 2820 mAh/g; since the voltage of the cell is about 1, the specific energy of this system is 2820 Wh/kg. If one calculates the energy density based on the end product NaBO₂,
 5 the energy density is lower, about 1620 Wh/kg.

In the case of the Li/water cell, the hydrogen generation proceeds by an electrochemical reaction believed described by:



In this case, the energy of the chemical reaction is converted to electrical energy in a 3
 10 volt cell, followed by conversion of the hydrogen to water in a fuel cell, giving an overall cell reaction believed described by :



where all the chemical energy is theoretically converted to electrical energy. The energy density based on the lithium anode is 3830 mAh/g at a cell potential of about 3
 15 volts which is 11,500 Wh/kg (4 times higher than NaBH₄). If one includes the weight of water needed for the reaction, the energy density is then 5030 Wh/kg. If the energy density is based on the weight of the discharge product, LiOH, it is then 3500 Wh/kg, or twice the energy density of the NaBO₂ system. This can be compared to previous concepts where the reaction of lithium metal with water to produce hydrogen has also
 20 been considered. In that scenario the energy density is lowered by a factor of three, since the majority of the energy in the Li/H₂O reaction is wasted as heat, and the energy density is based on a cell potential for the H₂/O₂ couple (as opposed to 3 for Li/H₂O) which in practice is less than one. In this embodiment of the present invention, illustrated in Fig. 7, the production of hydrogen can also be carefully
 25 controlled by load across the Li/water battery, the Li/water battery has a long shelf life due to the protective membrane, and the hydrogen leaving the cell is already humidified for use in the H₂/air fuel cell.

Conclusion

Although the foregoing invention has been described in some detail for
 30 purposes of clarity of understanding, it will be apparent that certain changes and modifications may be practiced within the scope of the invention. In particular, while

the invention is primarily described with reference to a lithium metal, alloy or intercalation anode, the anode may also be composed of any active metal, in particular, other alkali metals, such as sodium. It should be noted that there are many alternative ways of implementing both the process and compositions of the present invention. Accordingly, the present embodiments are to be considered as illustrative and not restrictive, and the invention is not to be limited to the details given herein.

All references cited herein are incorporated by reference for all purposes.

What is claimed is: